Latest Results From The CDMS-II Cold Dark Matter Search

P.L. Brink[*], D.S. Akerib[†], M.S. Armel-Funkhouser[**], M.J. Attisha[‡], C.N. Bailey[†], L. Baudis[§], D.A. Bauer[¶], R. Bunker[‖], B. Cabrera[*], D.O. Caldwell[‖], C.L. Chang[*], M.B. Crisler[¶], P. Cushman[††], M. Daal[**], R. Dixon[¶], M.R. Dragowsky[†], D.D. Driscoll[†], L. Duong[††], R. Ferril[‖], J. Filippini[**], R.J. Gaitskell[‡], R. Hennings-Yeomans[†], D. Holmgren[¶], M.E. Huber[‡‡], S. Kamat[†], A. Lu[**], R. Mahapatra[‖], V. Mandic[**], J.M. Martinis[§§], P. Meunier[**], N. Mirabolfathi[**], H. Nelson[‖], R. Nelson[‖], R.W. Ogburn[*], T.A. Perera[†], E. Ramberg[¶], A. Reisetter[††], R.R. Ross[**,¶¶], T. Saab[*], B. Sadoulet[**,¶¶], J. Sander[‖], C. Savage[‖], R.W. Schnee[†], D.N. Seitz[**], B. Serfass[**], K.M. Sundqvist[**], J-P.F. Thompson[‡], G. Wang[†], S. Yellin[‖,*] and B.A. Young[***]

[*] *Department of Physics, Stanford University, Stanford, CA 94305, USA*
[†] *Department of Physics, Case Western Reserve University, Cleveland, OH 44106, USA*
[**] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[‡] *Department of Physics, Brown University, Providence, RI 02912, USA*
[§] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*
[¶] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[‖] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[††] *School of Physics & Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*
[‡‡] *Department of Physics, University of Colorado at Denver and Health Sciences Center, Denver, CO 80217, USA*
[§§] *National Institute of Standards and Technology, Boulder, CO 80303, USA*
[¶¶] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[***] *Department of Physics, Santa Clara University, Santa Clara, CA 95053, USA*

Abstract. The CDMS-II collaboration's Cold Dark Matter search presently sets the most competitive exclusion limit in the world for the direct detection of the hypothesized Weakly Interacting Massive Particles (WIMPs) that constitute the cold dark matter of the Universe. Our experiment utilizes Ge (and Si) crystals as the target detectors, each with a mass of 250 g (100 g) and cooled to 30 mK. To eliminate natural radioactive sources as background the experiment is conducted in a well-shielded environment in the Soudan Mine, Minnesota, and has been operating for the last two years. To aid in the identification of a possible WIMP-candidate event, the detectors are designed to measure both the ionization and athermal phonon signals produced by each candidate event. The athermal phonon signal is measured using superconducting aluminum films on the crystal surface connected to tungsten transition edge sensors. The latest WIMP-search results from Soudan will be presented, along with projections for the future.

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INTRODUCTION

The Cryogenic Dark Matter Search (CDMS) collaboration[1] is performing an on-going direct-search experiment for the Weakly Interacting Massive Particles (WIMPs) that could constitute the majority of the 'cold dark matter' mass of the Universe[2]. The scientific case for WIMPs continues to grow stronger. Most compelling are WMAP results[3], in conjunction with studies of large-scale galactic clustering and supernova data[4]. One attractive WIMP candidate is the lightest supersymmetric particle (LSP) which arises naturally in many supersymmetric extensions of the Standard Model of particle physics, assuming that R-parity is conserved[5]. WIMPs are expected to interact elastically with nuclei, generating a recoil energy of a few tens of keV, at a rate lower than 1 event per kg per day[6].

Recently, CDMS published their first WIMP-search results from a new deep site in the Soudan mine, Minnesota[1]. These results (shown here in Fig. 1) set a new WIMP-nucleon cross-section exclusion limit, with a factor of four greater sensitivity than other compet-

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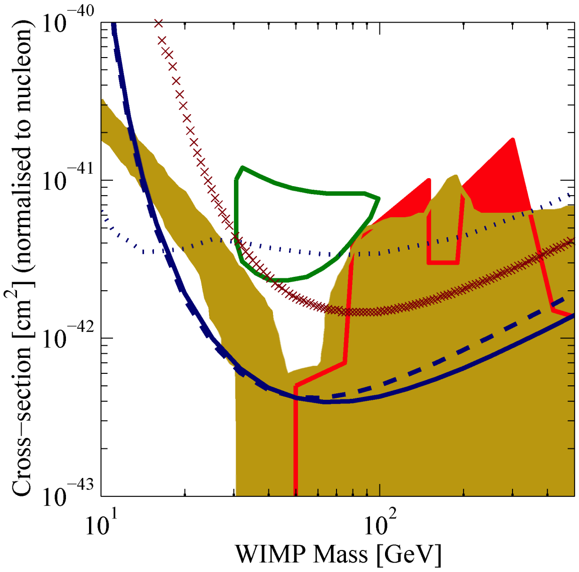

FIGURE 1. First WIMP-exclusion limit from CDMS II at Soudan [1]. Parameter space for the WIMP-nucleon scalar cross-section is excluded at 90% C.L. above the solid (and dashed) curves. Theoretical predictions from some Supersymmetry models are indicated by the dark grey (red) [8] and light grey (gold) [9] shaded regions. Also shown are earlier limits from CDMS at SUF (dots)[10] and EDELWEISS (×'s)[11]. The original DAMA (1-4) 3σ annual modulation signal[12] is shown as a closed contour under the same standard galactic and nuclear cross-section model assumptions.

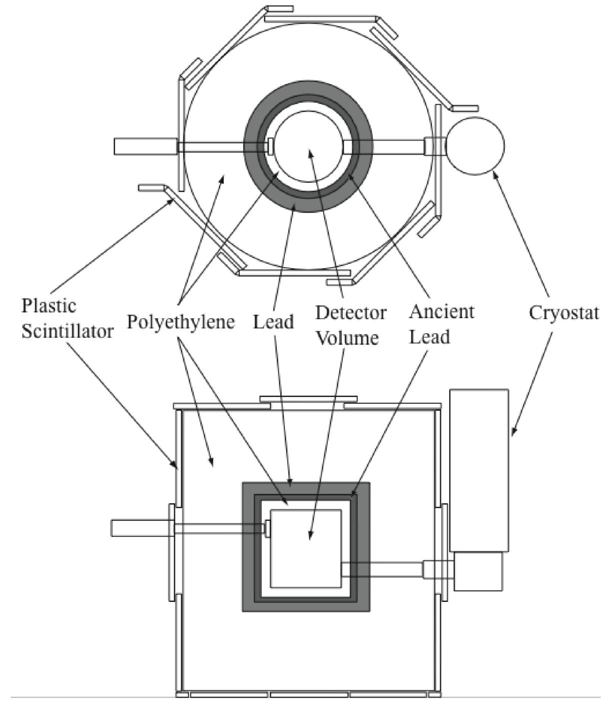

FIGURE 2. Schematic plan and side elevations of the shielding layers and muon-veto system surrounding the detector volume, with the dilution refrigerator outside of the shielding to the right. The refrigerator is connected to the detector volume, or "icebox", by the cold stem — a set of concentric OFHC copper cylinders thermally linked to each thermal layer of cooling power in the fridge. The stem coming out of the icebox to the left and also penetrating the shielding layers is the electronics stem and contains the wiring that connects the cold electronics and detectors to the room-temperature electronics.

ing direct-search WIMP experiments. The subsequent CDMS data run (Run 119) in mid-2004 with two towers each containing six detectors will be published shortly[7].

In this paper we will describe the experimental apparatus at Soudan that gave the impressive first results shown in Fig. 1, and report on the present activities to further extend our WIMP search. Finally, we will also briefly comment on our future WIMP-search plans to explore the realm strongly favored by supersymmetric theories.

EXPERIMENTAL APPARATUS

In order to perform a direct-detection WIMP search it is necessary to eliminate or actively discriminate against sources of natural radioactivity that could mimic a WIMP event occurring in the target material of interest. First, the CDMS II apparatus is shielded by an earth overburden of 780 m by its location in the Soudan Underground Laboratory[13].

The residual cosmic-ray muon flux incident on the passive shielding surrounding the detector volume is vetoed against by an active plastic scintillator veto system, as shown in Fig. 2. Muons interacting in nearby cavern rock may produce high energy neutrons that could penetrate the shielding and register a WIMP-like event in the detectors, without the associated cascade triggering the muon veto system. This background became the limiting background for the original CDMS I experiment sited at the Stanford shallow site [10]. However this source of background is not expected to be significant at the deeper depths of the Soudan mine for another two orders of magnitude WIMP-search exposure of the detectors, which is several years away.

As shown in Fig. 2, a significant amount of polyethylene shielding exists around the icebox. This is primarily to moderate the incident neutron energies, from (α, n) decays in the surrounding cavern rock, to undetectable levels[14]. The lead shielding present in the design reduces the ambient gamma flux and associated electrons ejected from nearby materials towards the detector surfaces. The detectors themselves can discriminate between bulk gamma events (the majority of the radioactive background) and nuclear recoil events (expected from both WIMPs, and any neutrons present) due to the simultaneous measurement[10] of both the ionization signal and phonon signal generated by an event. A possible contamination of the sought-after nuclear recoil events is surface-electron events. Thus CDMS II chose to deploy advanced Z-dependent Ionization and Phonon (ZIP) detectors[10] that could identify such events by their faster athermal phonon signals[15]. In order for the detectors to operate they must be cooled to below 50 mK. Thus the presence in Fig. 2 of a dilution refrigerator connected to the set of copper cans (the icebox) that house the detectors. This design allowed the detectors to be operated in a radio-pure environment away from the dilution refrigerator.

The first six ZIP detectors constituting Tower 1 operated at Soudan are the same ones first run at the Stanford shallow site[10]. The CDMS detectors are sensitive to the athermal phonon flux generated shortly after an event. The sensitivity to the phonon flux before significant thermalization has occurred allows the identification of near-surface events due to the enhanced phonon decay and more rapid arrival of the phonon flux in the sensors[15]. Events within the top 1 μm of the detector surface tend to have a suppressed ionization yield, thus they could mimic the sought-after nuclear-recoil events, but the measurement of the athermal phonon signal's rapid risetime allows us to reject these undesired background events. A similar detector concept is under development for the EDWELWEISS-II experiment[16] using Nb-Si films.

As shown in Fig. 3, the CDMS phonon sensors contain tungsten superconducting-normal transition edge sensors. These are photolithographically patterned thin-film sensors whose transition temperature is $\sim$ 100 mK. Although higher than the transition temperature of bulk, α-phase W, these sensors are ideal for the application of interest here. The athermal phonon signal is first absorbed by superconducting Al films on the crystal surface. The generated quasiparticles diffuse through the Al and thermalize in the W sensor's electron system, raising its temperature. As the sensors are voltage-biased within their own superconducting-normal transition there is an increase in the sensor resistance which is read out with SQUID-based current sensitive amplifiers[17]. More details on these "ZIP" detectors can be found in Refs [10, 14, 15].

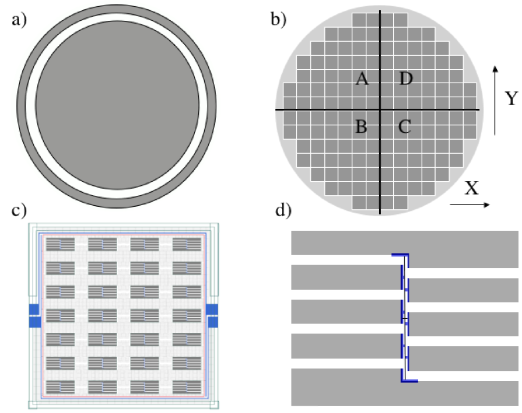

FIGURE 3. Schematic layout of a ZIP detector showing a) the ionization side and b) the phonon side on each face of the 3-inch diameter Ge or Si 1-cm thick substrates. a) The ionization side has a metallized grid segmented into a large inner and an outer (guard ring) electrode. b) The phonon-side is divided into four quadrants, labelled A, B, C and D, for each phonon signal readout channel. Each phonon channel consists of 37 (5 mm)^2 photolithographic sensor dies (dark grey). The area outside of the sensor dies (light grey) consists of a passive metallized Al/W grid similar to the ionization-side electrodes. c) Each phonon-side sensor die contains 28 athermal phonon sensors [15] . d) Each sensor consists of a 1 μm wide tungsten Transition Edge Sensor (TES) connected to 8 aluminum athermal-phonon collection fins.

PRESENT SOUDAN ACTIVITIES

Subsequent to the end of the two-tower run (Run 119), the cryostat at Soudan was warmed up in the latter half of 2004 to allow cryogenic upgrades and installation of three additional detector towers (see Fig. 4). The new towers required extra electrical wiring (copper-trace striplines) to be installed in the electronics stem for their read out. The heat-load of this extra wiring required the installation of a cryocooler (Sumitomo Heavy Industries RDK-415D) to intercept $\sim$ 1.5 W from the 4 K heat sink and $\sim$ 20 W from the 77 K head sink in the electronics stem.

A number of repairs were also implemented to remove previous leaks both from the liquid nitrogen cooling loop into the Outer Vacuum Chamber (OVC), and a more serious leak from the liquid helium bath into the OVC. Improvements were also implemented to increase the pumping capability on the OVC during the next run. Thus, reduced down-time due to thermal runaways is anticipated as we go forward.

A cooldown of the icebox was attempted in February 2005, but the condensor line of the dilution unit was blocked (by a fragment of the copper sinter filter upstream of the primary impedance). This required removal of the dilution fridge from the icebox, repairs to the dilution unit, three fridge-only cryogenic test runs, and then reattachment of the fridge to the icebox.

All the repairs were successful and the five detector towers were cooled down to a base temperature of 40 mK in mid-July 2005.

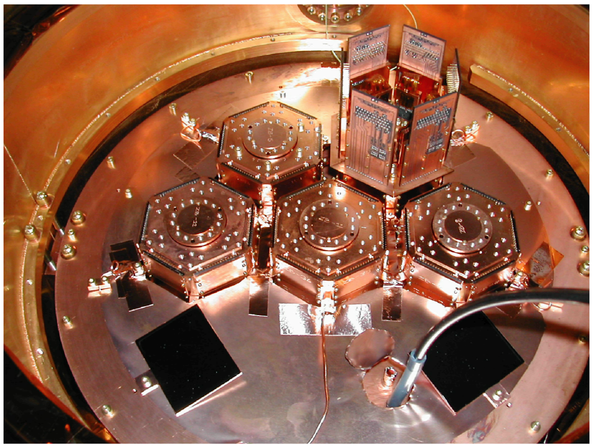

FIGURE 4. Installation of the five detector towers for the next WIMP-search run at Soudan in late 2004. The top sections of each (hexagonal) tower are visible with the cold electronics (FETs and SQUIDs) cards already installed on one of the towers. Underneath each tower (hidden from view by the 600 mK copper lid) are six ZIP detectors whose wiring from 10 mK to 4 K is contained within vacuum coax channels occupying one face of the tower for each detector. The two black "paddles" visible in the foreground are for thermalizing higher temperature IR photons. An old-air purge tube is also visible and suppresses the ambient radon gas background of the Soudan mine within the inner 10 mK can containing the ZIP detectors whilst the icebox is open.

FUTURE PROSPECTS

The present 5-tower WIMP-search run at Soudan with 4.5 kg of Ge and 1 kg of Si target material is funded for the remainder of 2005 and 2006, with possible extensions of operations if merited. The CDMS collaboration has recently proposed the SuperCDMS program[18], which will push the search for WIMPs to even higher sensitivities that coincide with searches for supersymmetric particles at the Large Hadron Collider (LHC). The reader is referred to Ref [18] for details of this program, with the Phase A project proposed to be 25 kg of Ge target material with an expected sensitivity (assuming no significant backgrounds) for a scalar WIMP-nucleon interaction cross-section of $2 \times 10^{-45}\mathrm{cm}^2$ at a 60 GeV/c^2 WIMP mass.

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